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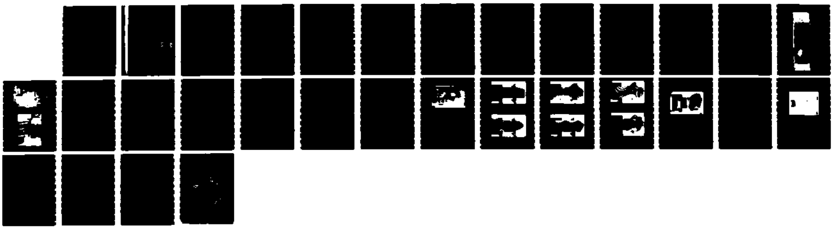

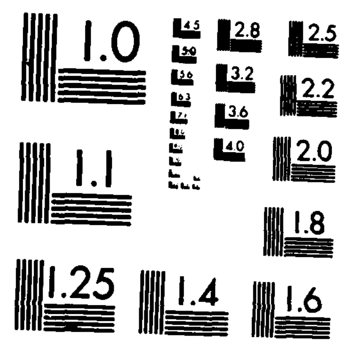

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Structures Technical Memorandum 438

DYNAMIC RESPONSE OF A GRAPHITE/EPOXY COMPOSITE PLATE

by

M. HELLER AND S. J. RUMBLE

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SUMMARY

The dynamic response of a graphite/epoxy composite plate has been characterized by a number of techniques to investigate their suitability for detection of barely visible impact damage (BVID). The investigations included single point accelerometer response, time-averaged holographic interferometry and thermoelastic analysis. It was found that the detection of BVID using vibration analysis is complicated by the sensitivity of the analysis to boundary conditions and the means of excitation. Further investigation would require larger specimens to reduce the effects of boundary conditions.

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CONTENTS

1. INTRODUCTION

Graphite/epoxy composites have many advantages as aircraft structural materials and for this reason their use is becoming increasingly widespread. However, graphite/epoxy composites are susceptible to a wide range of damage. In particular, impact can cause a significant amount of delamination, even though the only external indication of damage may be a very small surface indentation. For this reason, this type of damage is often referred to as "barely visible impact damage" (BVID). The development of improved and more efficient means of detecting such damage is important.

This paper investigates the potential for characterising the dynamic response of a graphite/epoxy composite plate to indicate the presence and possibly the location of BVID. A brief outline of vibrational analysis is given in section 2. A more detailed discussion of vibration techniques applied to non-destructive testing has been included in a recent review by Adams.[1]

2. BACKGROUND

2.1 Modal Analysis

The dynamic response (i.e. natural frequencies, modal dampings, and mode shapes) of a continuous structure depends on the distribution of inertia and stiffness throughout the structure. If the structure is damaged (e.g. BVID in a composite plate) then whilst the inertia distribution will remain the same, the stiffness distribution, and hence the dynamic response of the structure, will be altered. Characterisation of this change in dynamic response through measurement of either natural frequencies, modal damping or mode shapes may be a useful means to detect the presence and possibly the locations of damage in a composite plate. Several methods used for this purpose are given below.

2.2 Single Point Accelerometer Response

When excited at a natural frequency, a continuous multiple degree of freedom (D.O.F.) structure will behave as if it has only one D.O.F.[2] assuming that the structure is relatively linear, has low damping and has low modal density. As the law of superposition is also obeyed, all natural frequencies can be obtained by excitation with white noise using digital vibration analysis equipment, provided excitation is not at a node.

2.3 Holography

The technique of time averaged holographic interferometry permits visualization of the amplitude distribution for a given vibrational mode. A photograph of a holographic reconstruction of a vibrating object shows darkened regions over the object surfaces. These darkened and corresponding lighter regions are interference fringes. The interference fringes can be considered to form a type of contour map of the peak to peak displacement of the object's surface during vibration in a given mode. The zero displacement points or nodes are always a light fringe and can be easily identified as they are the brightest fringes. Detailed treatments of the theory of holographic interferometry have been presented in numerous texts. (3),(4)

2.4 Thermoelastic Analysis

The thermoelastic effect, which was first investigated by Lord Kelvin in 1853, states that within the elastic range, a body subjected to tensile or compressive stresses experiences a reversible conversion between mechanical and thermal forms of energy. This effect has been utilised in a commercially available instrument named SPATE 8000. This instrument measures the change in stress in a structure undergoing constant amplitude cyclic loading. The structure is scanned to give its stress distribution, and hence the mode shape at a particular frequency can be determined.

3. SPECIMEN

The material designation of the graphite/epoxy composite plate used in the testing program was XAS fibre/914 resin. The layup of the plate was $(\pm 45/0_2)_{3S}$ and its in-plane dimensions were 73mm X 225mm with its thickness being approximately 2.9mm. Various tests were carried out, both before and after the introduction of impact damage to the specimen.

A suitable amount of impact damage was imparted on the back face of the specimen by using an ARL impact rig to drop a 9 kg impactor from a height of 0.5m on to the specimen which was firmly clamped to a support structure. The impact weight and drop height to produce the required amount of BVID were determined by carrying out trials on spare pieces of the test material. The specimen was C-scanned before impacting to confirm that it was undamaged, and also after

impacting to determine the amount of damage. The C-scan obtained after damage is shown in Fig. 1. This Figure shows the damage on a plane at 0.9 of the thickness from the impacted face and this was the plane of maximum damage. The spanwise length of this damaged region was approximately 40 mm which constitutes a significant degree of damage.

4. SINGLE POINT ACCELEROMETER RESPONSE

The excitation source used in these tests was the periodic random output of a HP3582A Fourier analyser. The excitation was fed to an ARL high output impedance power amplifier which in turn drove a Ling 409 electromagnetic shaker. The response was measured using a PCB309-A accelerometer and analysed using a Nicolet 411B analyser. The analysed data were subsequently stored on a NOVA3 minicomputer and plotted on a Tektronix 4662 plotter. The specimen was mounted in a clamping arrangment at one end as shown in Figs. 2 and 3, the excitation force being applied laterally at the other end on the back face of the specimen. The mounting position of the accelerometer is also clearly shown. Accelerometer response data were first recorded and analysed with the shaker and specimen in an initial condition.

To investigate the influence of damping and excitation conditions the specimen was removed and then put back and further data recorded. Data were then recorded after the specimen had been removed and damaged. The analysis consisted of determining the response curves for various freuqency ranges and also estimating the damping of various modes using an available computer program.

Tests to investigate the sensitivity of the response parameters to the loading point were carried out for the specimen in the undamaged condition. The various loading points considered are shown in Fig. 4.

Frequency reponse plots for the range 0 to 500Hz are given in Fig. 5, while the plots for the ranges 0 to 2000Hz and 0 to 5000Hz are given in Figs. 6 and 7 respectively.

Plots obtained for the different excitation point cases are given in Fig. 8. In Table 1 damping values are given for some modes for the four sets of data recorded. A typical plot for these damping calculations is given in Fig. 9. In this plot, the complex response, i.e., the magnitude of the response and the phase angle between force and the response, has been plotted at a number of frequencies, and for

two modes. The smooth curves were the results of least squares fits of the data to a mathematical model used to estimate the dampings.

5. HOLOGRAPHY

The time-averaged holograms were recorded with the specimen undergoing single frequency excitation. The excitation source was a MUIRHEAD D-88-A two phase oscillator whose 0, (in phase) output was used to directly drive the Ling 409 electromagnetic shaker. The 90, output from the oscillator and the accelerometer response were displayed in X-Y mode on an oscilliscope. The frequency and output level of the oscillator were adjusted to give approximately 1 to 1.5 μm peak to peak displacement at the accelerometer with the specimen vibrating in one of its modes.

The holograms were recorded on Agfa 8E56 holographic plates using the 514.5 nm green line from an argon laser with a one to one ratio between the reference and object intensities at the plate. The 8E56 plates were exposed for 3 seconds which would have corresponded to ND2 to ND2.5 after fixing. However, in this work phase holograms were created by using a reversal bleach technique[5].

The arrangement of the optical components, shaker and specimen is shown in Figs. 10 and 11. The limited area available and specimen size necessitated the use of two plane mirrors to gain maximum expansion and hence uniformity of the specimen and plate illumination beams.

Photographs of the holograms taken of various modes before and after damage are given in Figs. 12 to 18.

6. THERMOELASTIC ANALYSIS

The excitation equipment for this work was similar to that described in Section 4, except that to vibrate the specimen at a natural frequency the sinusoidal output of a Solartron Frequency Response Analyser was used as the excitation source. The clamping conditions were different to those described in Section 4. For this work the specimen was clamped to the shaker at one end and the other end was free, as shown in Fig 19. Stress data were recorded for a number of modes using the SPATE 8000. A photograph of a typical stress contour for a mode at 81 Hz is given in Fig. 20 for the undamaged specimen.

7. DISCUSSION

The data in Fig. 8 show that the modal frequencies and relative magnitudes of the response peaks are quite sensitive to excitation locations, for the shaker and coupling system used. This indicates that the excitation system has made a signifcant contribution to the stiffness and mass distribution of the specimen and shaker system. From Fig. 5 it can be seen that the four sets of response data are very similar. The modal frequencies are virtually identical. However, there are slight differences in relative response amplitudes for particular modes between data sets. It is not possible to use these results to indicate the presence of damage. Fig. 6 indicates more complex response behaviour for all 4 cases. Between cases, modal frequencies are quite different, and the number of modes varies, as do the relative magnitudes of the response peaks. For this reason it is not possible to separate changes due to damage or removing. For Fig. 7 similar comments apply as for Fig. 6 in the region 2000 - 5000 Hz.

The estimates of the dampings, contained in Table I, were made for the frequency regions which appeared to be least sensitive to the excitation location. The changes in dampings of the two modes in the 300-370 Hz region do not show any correlation with damage. In the 1050-1150 Hz region there is an indication that damping increases with damage. However, a definite conclusion that the damping increase indicates the presence of damage cannot be reached for the following reasons. There are significant differences in response of the 1050 Hz mode compared to the 300-350 Hz region in the two damaged specimen cases. Also, the number of modes for which a reliable damping estimate could be calculated, was signficantly different between the damaged and undamaged cases.

Whilst only a limited number of time-averaged holographic reconstructions for the undamaged specimen are shown here (Figs. 12-15), it was demonstrated that mounting condition and excitation had a significant effect on mode shapes. However, holograms recorded after damage showed perturbations of the fringes near the damage location, indicated by an arrow in Figs. 16-18.

A typical stress contour obtained using the SPATE 8000, for the undamaged specimen is shown in Fig. 20. This contour shows the specimen in a fundamental bending mode, with the highest stress occuring at the clamping location and reducing to zero towards the other end. The pink region on the top right hand corner is the location of the accelerometer. For this work it was only possible to

obtain suitable stress contours for low frequency modes. This was because of the difficulty of obtaining large enough displacements and hence stresses at the higher frequency modes for this specimen. Due to these difficulties, and as the lower frequency modes were considered unlikely to indicate damage, no thermoelastic analysis was carried out for the damaged specimen.

8. CONCLUSION

A vibration analysis of a graphite/epoxy composite plate was used to try to detect BVID. It was found that the sensitivity of the vibration analysis to changes in boundary conditions and means of excitation caused these two aspects to dominate any change due to damage.

The mode shapes as indicated by holographic interferometry also showed that changes in boundary conditions appear to dominate changes due to damage. However, damage could be observed as perturbations to nearby fringes.

Thermoelastic analysis was found to be unsuitable for the detection of mode shapes other than low frequency modes, due to the difficulty in obtaining reasonable magnitudes of displacement for higher frequency modes.

Further investigation of vibration analysis applied to BVID detections would require larger specimens to reduce the effects of boundary conditions, or that the boundary conditions are kept constant.

This would require the damage to be applied in-situ. A better means of excitation would also be required to improve the detectability of BVID using vibration analysis.

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2. K. H. Heron, D. R. Gaukroger, C. W. Skingle. The derivation of equations of motion from response data and its application in flutter testing. Royal Aircraft Establishment Technical Report 73051, June 1973.

3. C. M. Vest. Holographic Interferometry, John Wiley, 1979.

4. P. Hariharan. Optical Holography; Principles, techniques and applications, Cambridge University Press, 1984.

5. Ibid, page 99

TABLE I ESTIMATED DAMPING OF MODES FOR SPECIMEN UNDAMAGED AND DAMAGED

Specimen Condition	Estimated frequency of mode (Hz)	Estimated damping of mode (% of critical)
Undamaged, before removal	335.3	0.4
	370.7	0.4
	1080.0	0.7
	1136.0	0.5
Undamaged - after removal and remounting	334.7	0.4
	369.3	0.3
	1022.6	1.9
	1111.8	0.4
	1140.1	0.6
Damaged - before removal	334.9	0.4
	370.3	0.3
	1055.1	0.9
Damaged - after removal and remounting	332.4	0.5
	368.1	0.4
	1055.1	0.9

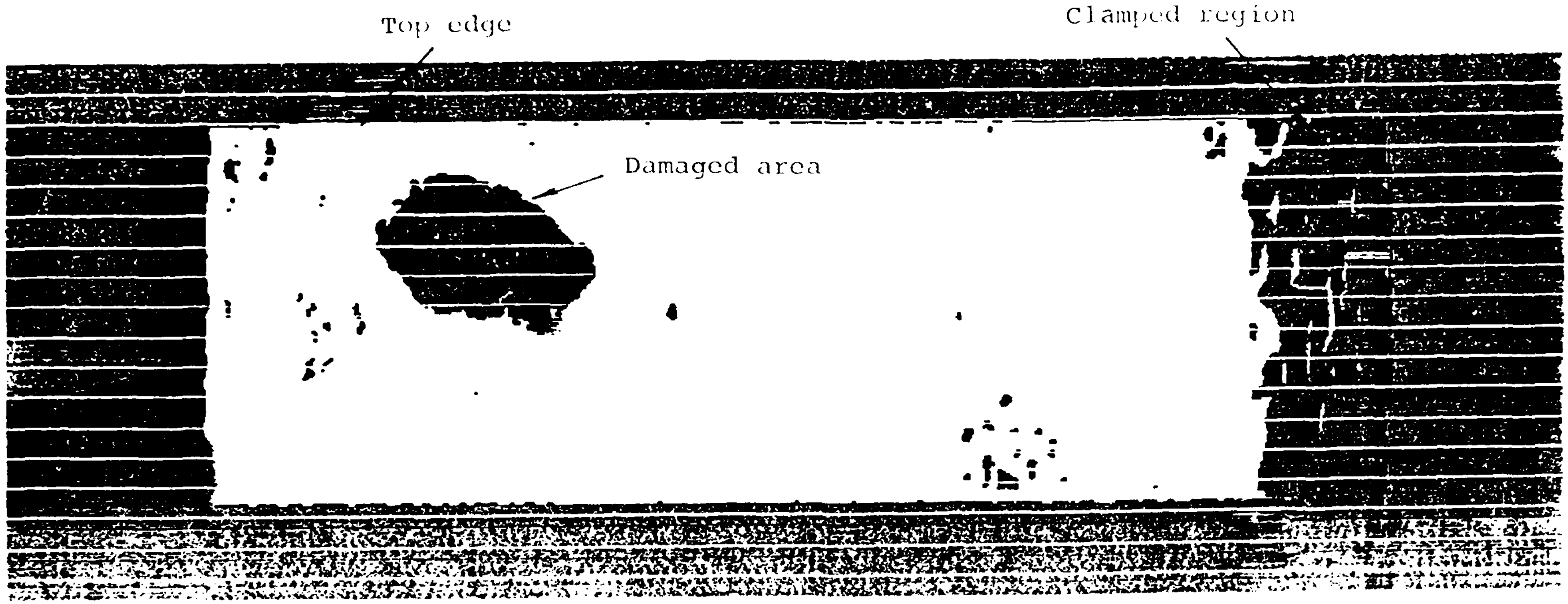


FIG.1 C-SCAN OF SPECIMEN AFTER IMPACT DAMAGE AT 0.9 OF SAMPLE THICKNESS.

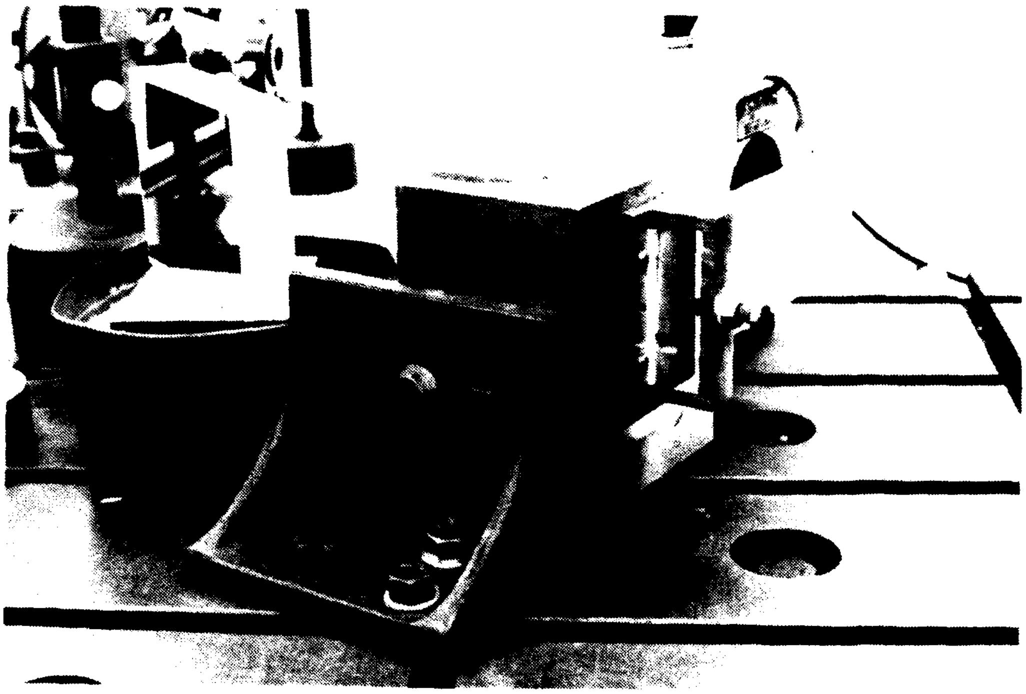


FIG.2 SPECIMEN CLAMPING ARRANGEMENT

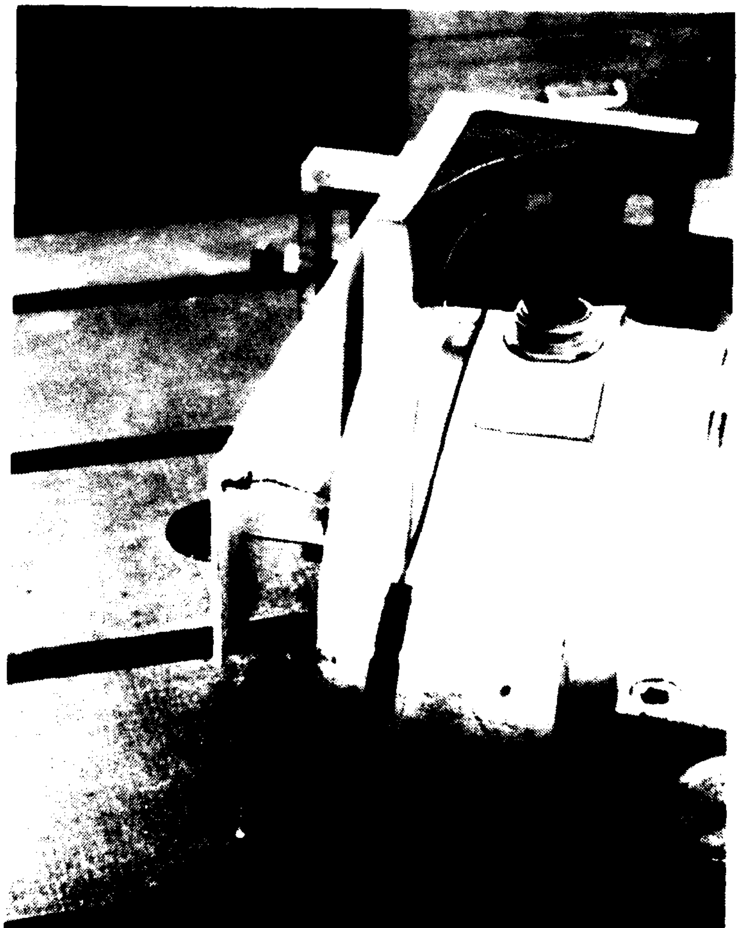


FIG.3. SPECIMEN EXCITATION ARRANGEMENT

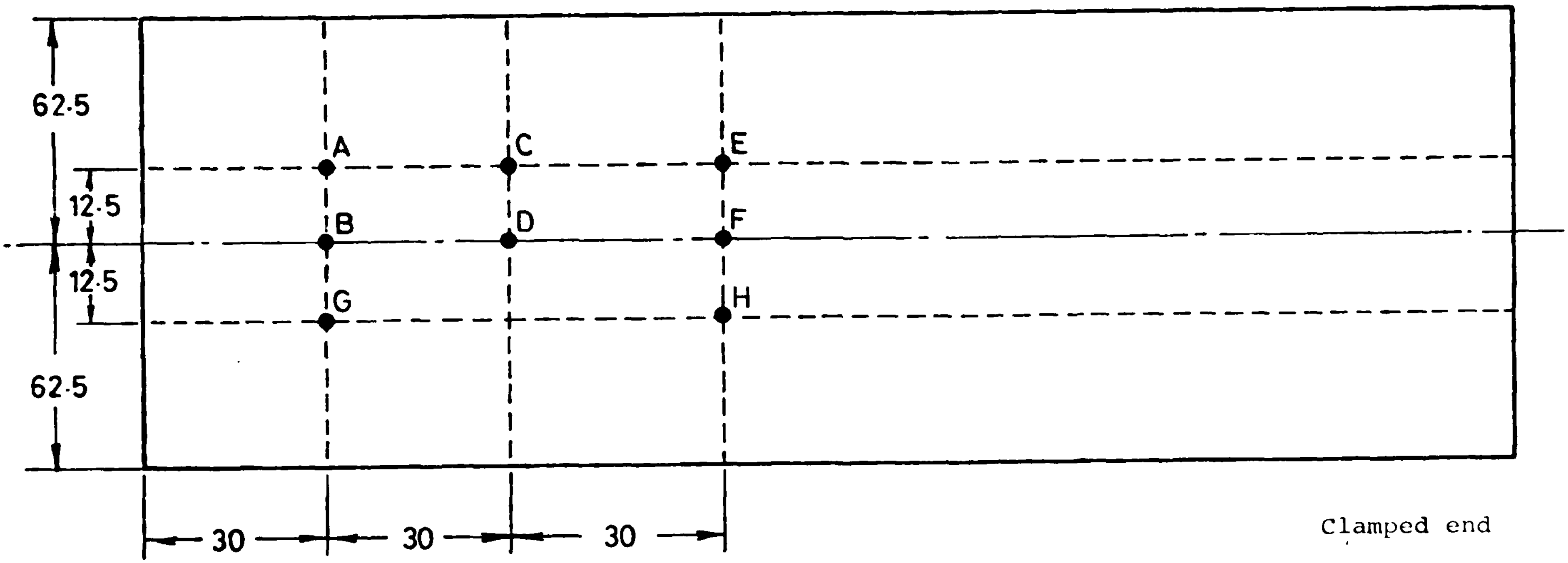
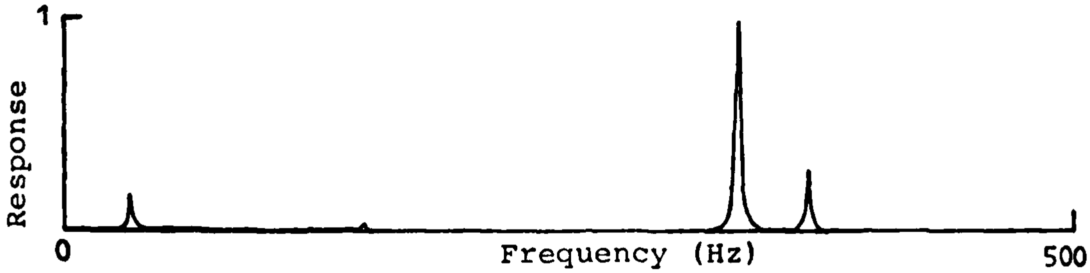
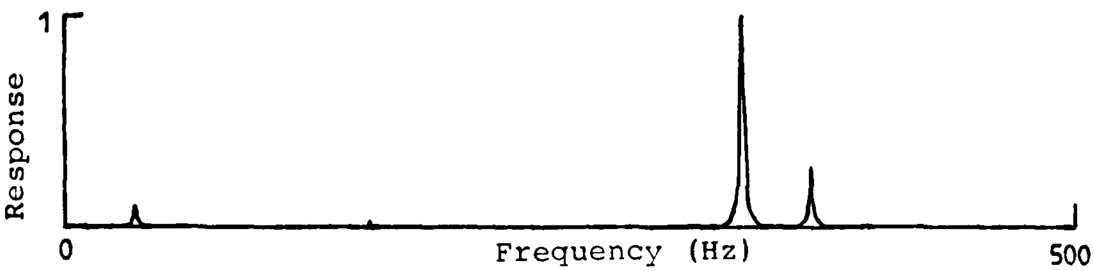


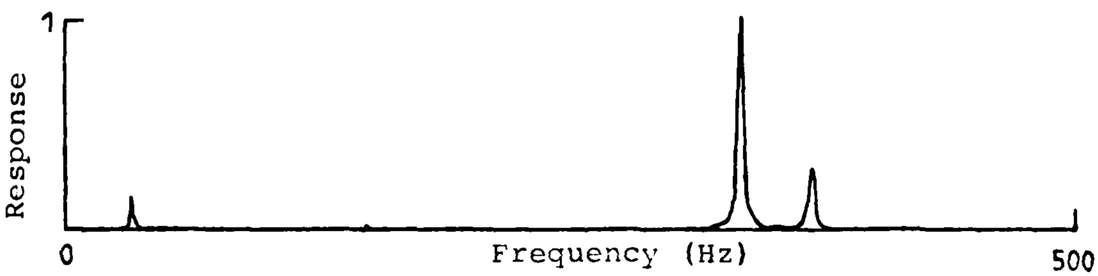
FIG.4 LOCATIONS OF VARIOUS EXCITATION POINTS



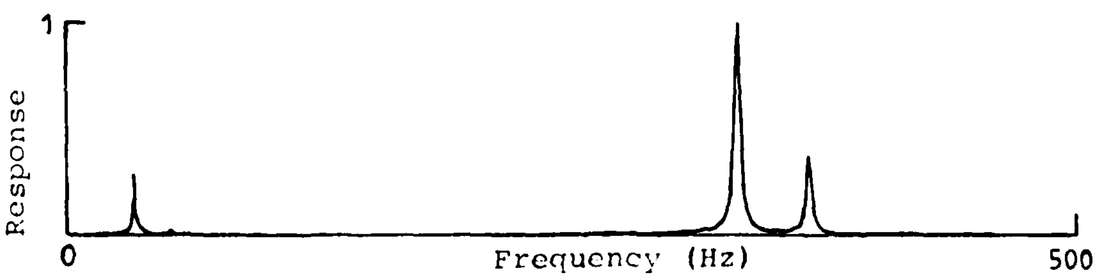
(a) Specimen undamaged - before removal



(b) Specimen undamaged - after removal
and remounting

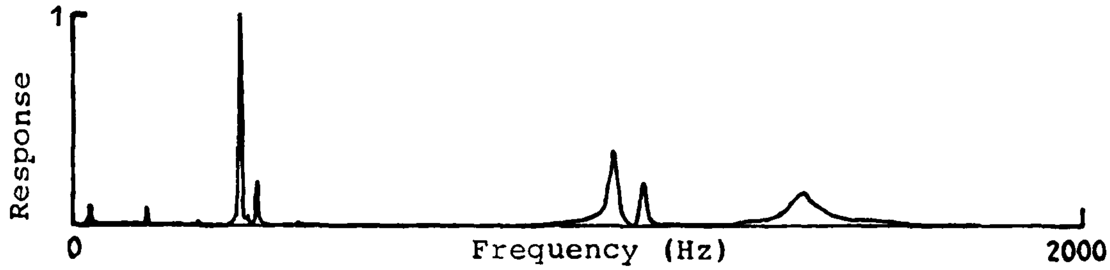


(c) Specimen damaged - before removal.

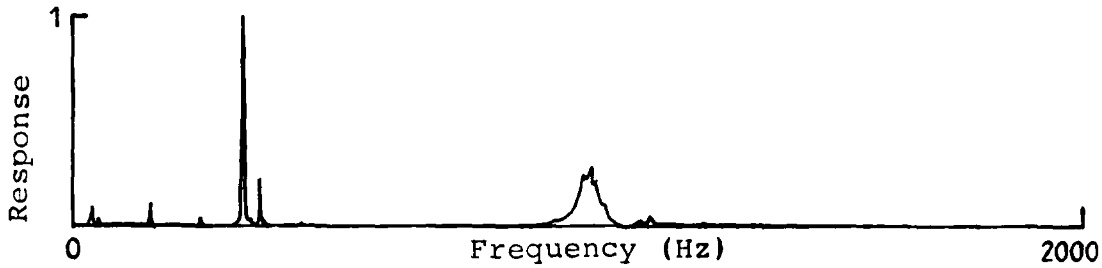


(d) Specimen damaged - after removal
and remounting.

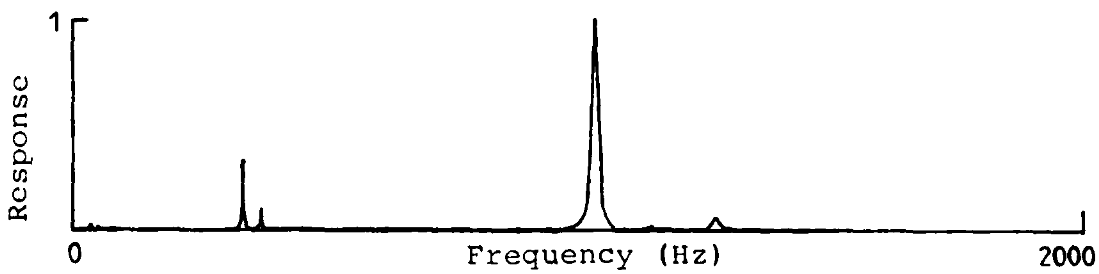
FIG.5 NORMALISED RESPONSE OF SPECIMEN TO WHITE NOISE IN FREQUENCY RANGE 0 Hz TO 500 Hz.



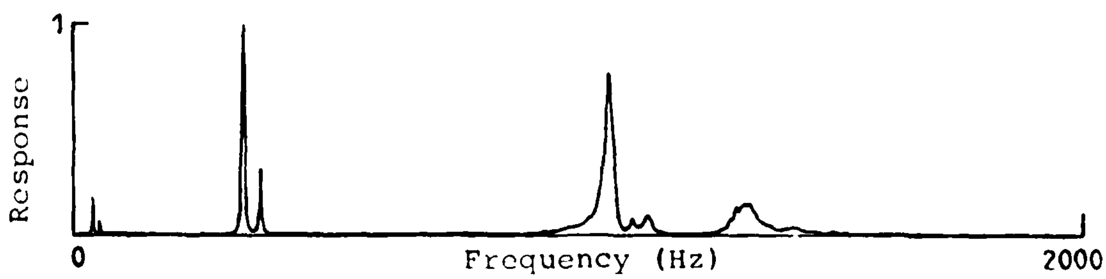
(a) Specimen undamaged - before removal



(b) Specimen undamaged - after removal



(c) Specimen damaged - before removal



(d) Specimen damaged - after removal and remounting

FIG. 6 NORMALISED RESPONSE OF SPECIMEN TO WHITE NOISE IN FREQUENCY RANGE 0 Hz TO 2000 Hz.

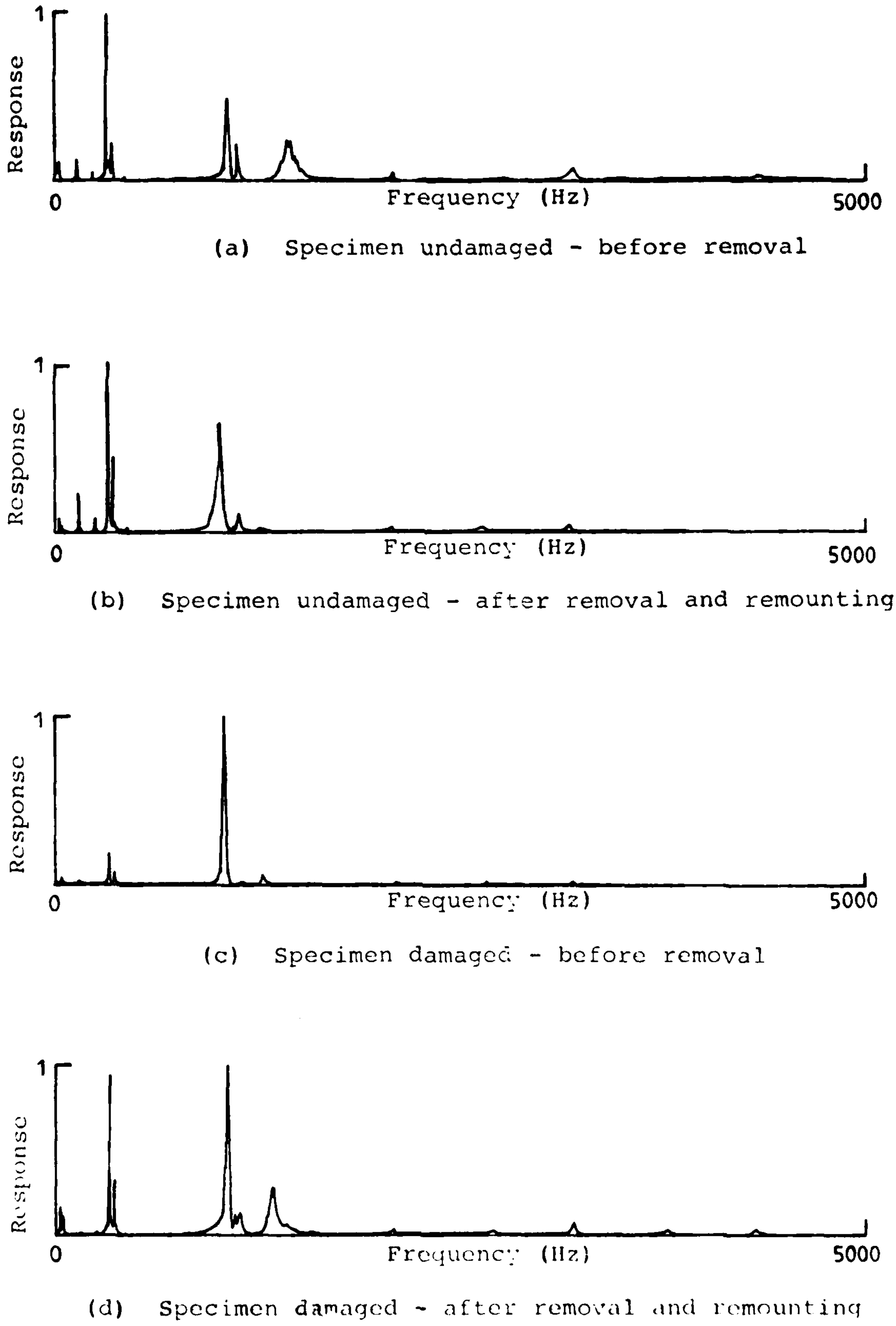


FIG. 7 RESPONSE OF SPECIMEN TO WHITE NOISE IN FREQUENCY RANGE 0 Hz to 5000 Hz,

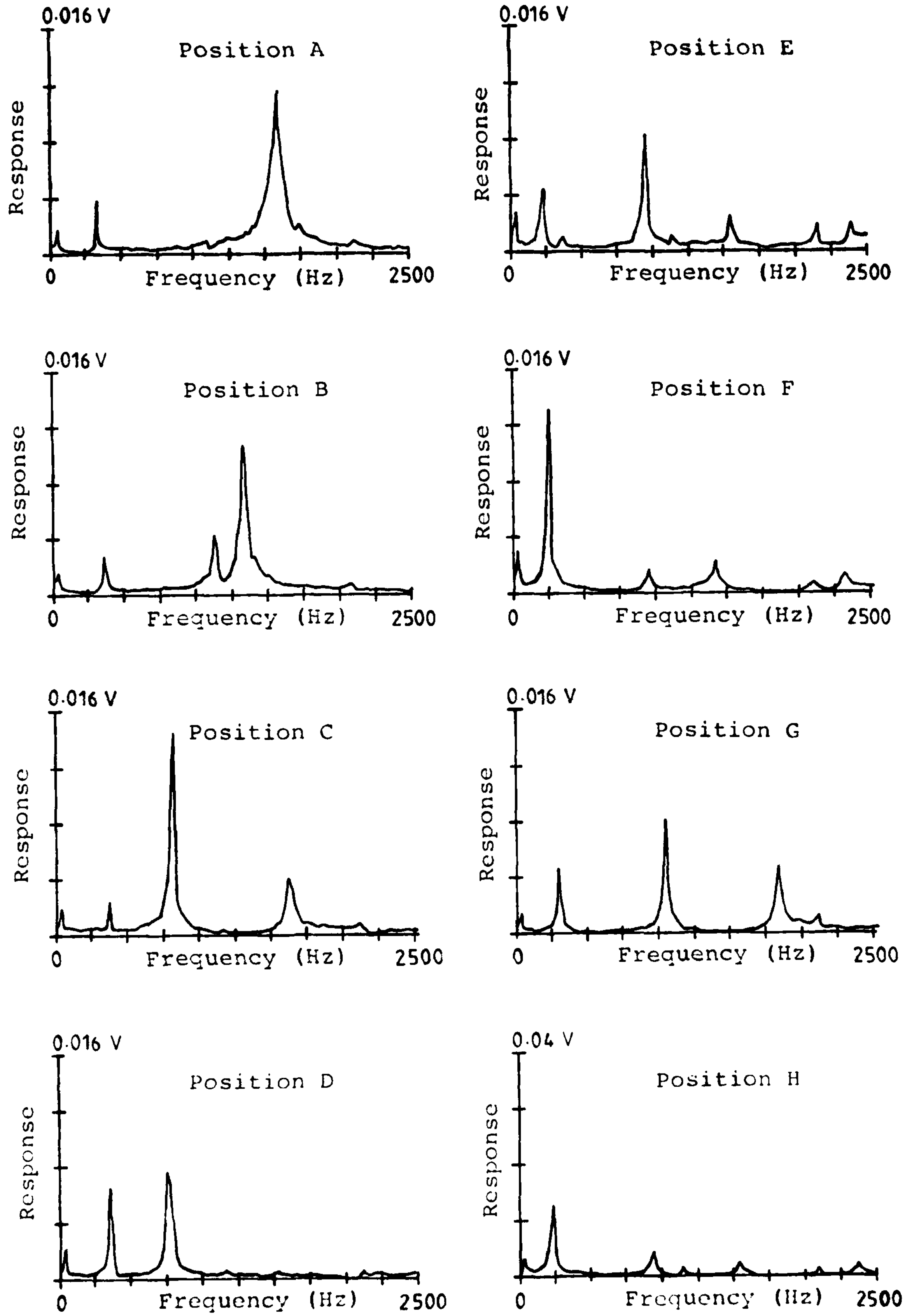


FIG.8 ACCELERATION RESPONSE CURVES OF UNDAMAGED SPECIMEN FOR POINT EXCITATION AT POSITIONS (A) TO (H).

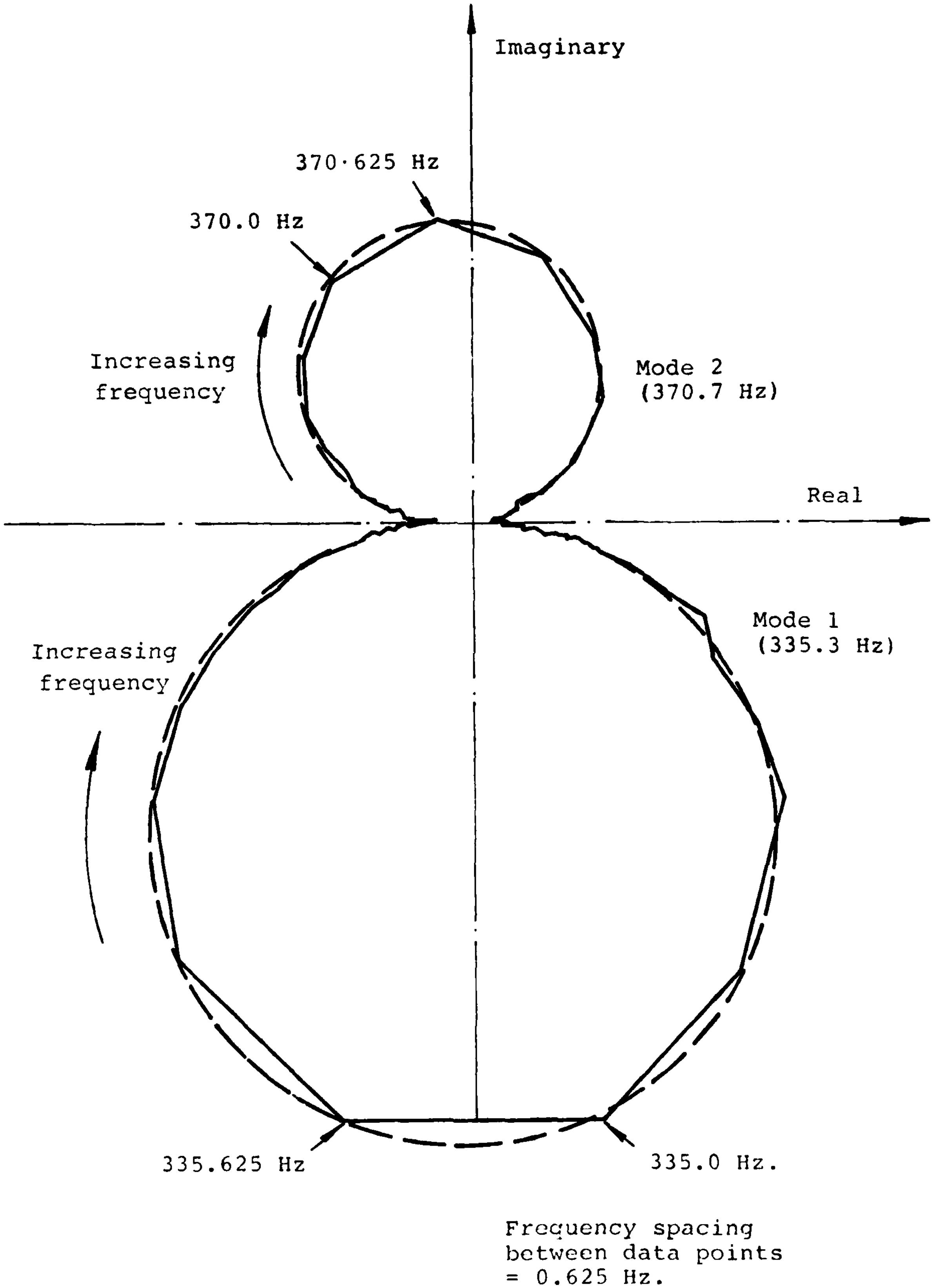


FIG. 9 TYPICAL NYQUIST PLOT FOR DAMPING ESTIMATION OF TWO MODES.
(Specimen undamaged - before removal)

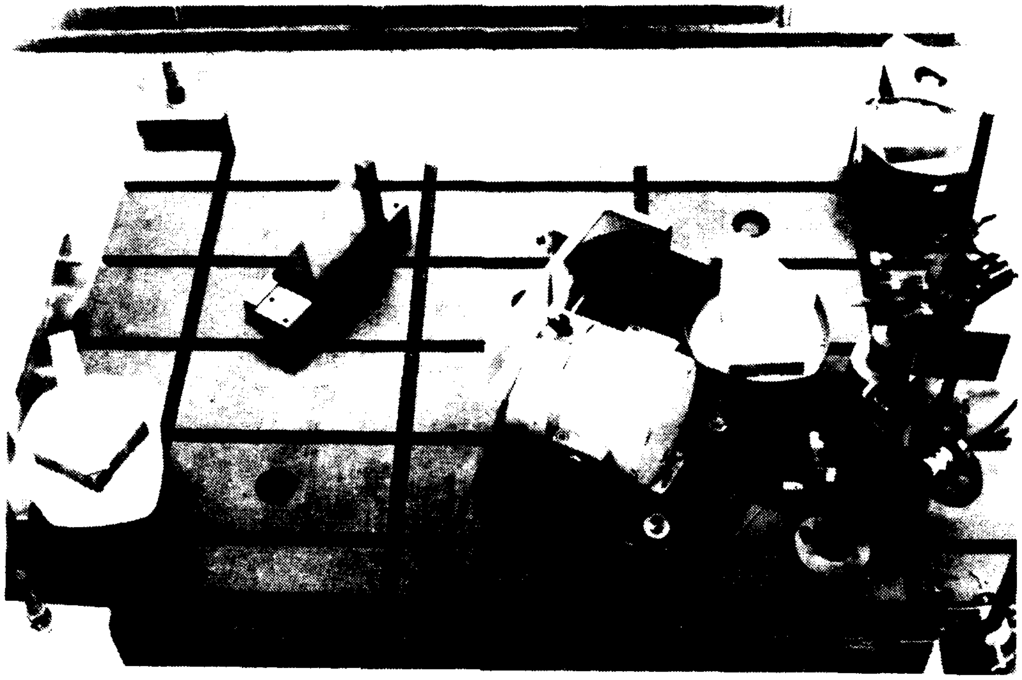


FIG.10 ARRANGEMENT OF OPTICAL COMPONENTS

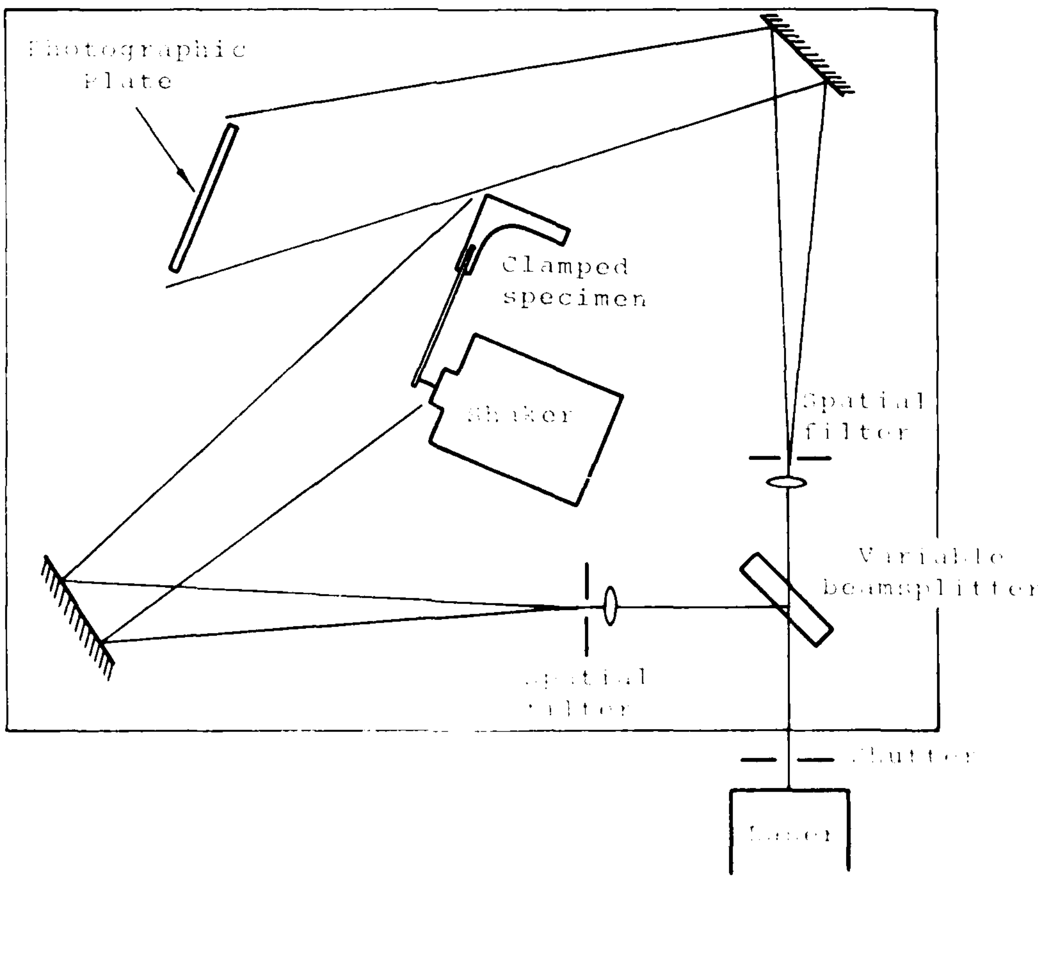
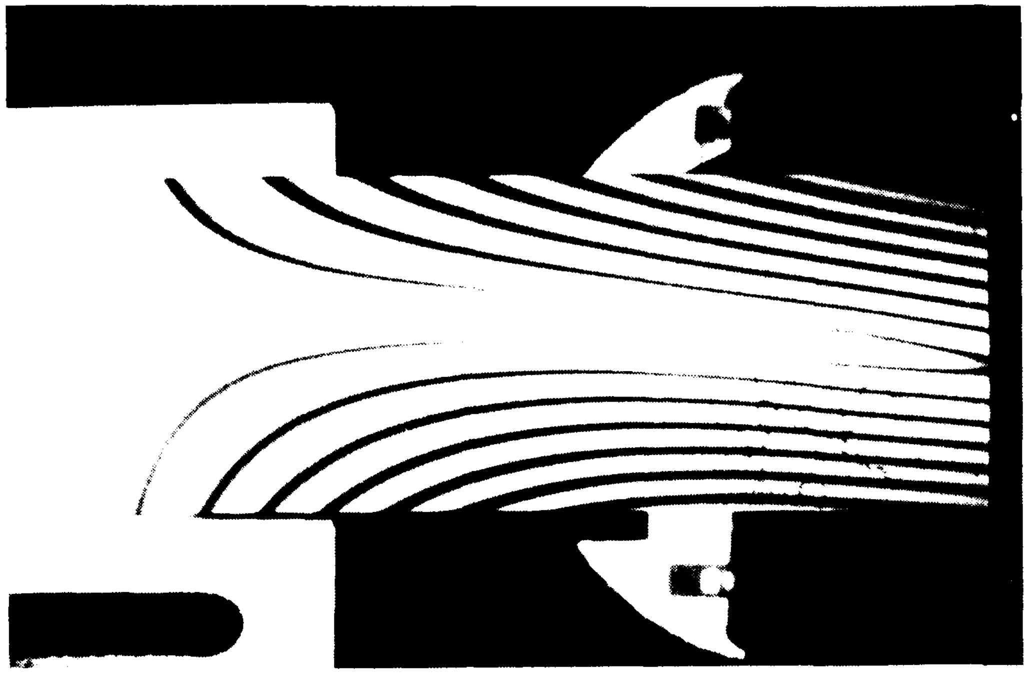


FIG.11 SCHEMATIC DIAGRAM OF OPTICAL ARRANGEMENT



FIG,12 HOLOGRAM AT 434 Hz FOR UNDAMAGED SPECIMEN

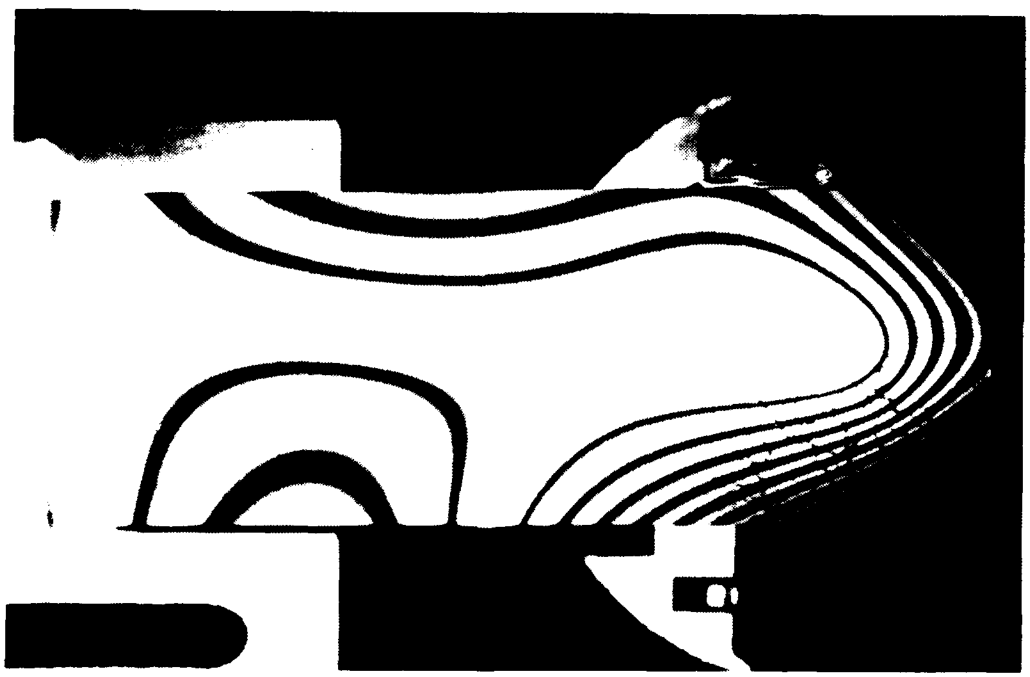


FIG.13 HOLOGRAM AT 1125 Hz FOR UNDAMAGED SPECIMEN

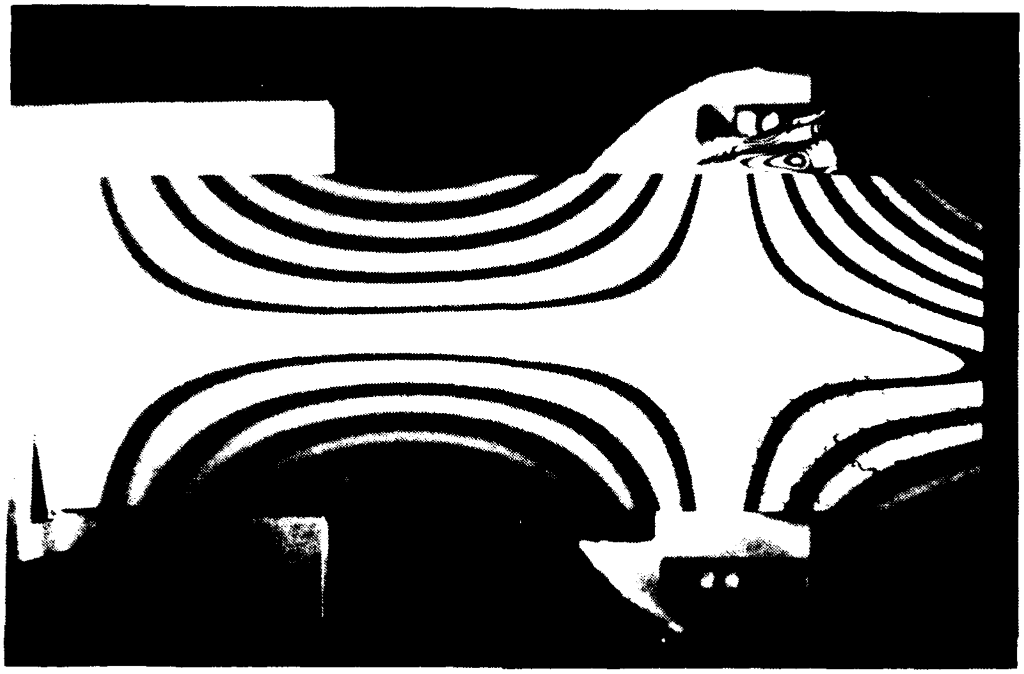


FIG.14 HOLOGRAM AT 1530 Hz FOR UNDAMAGED SPECIMEN

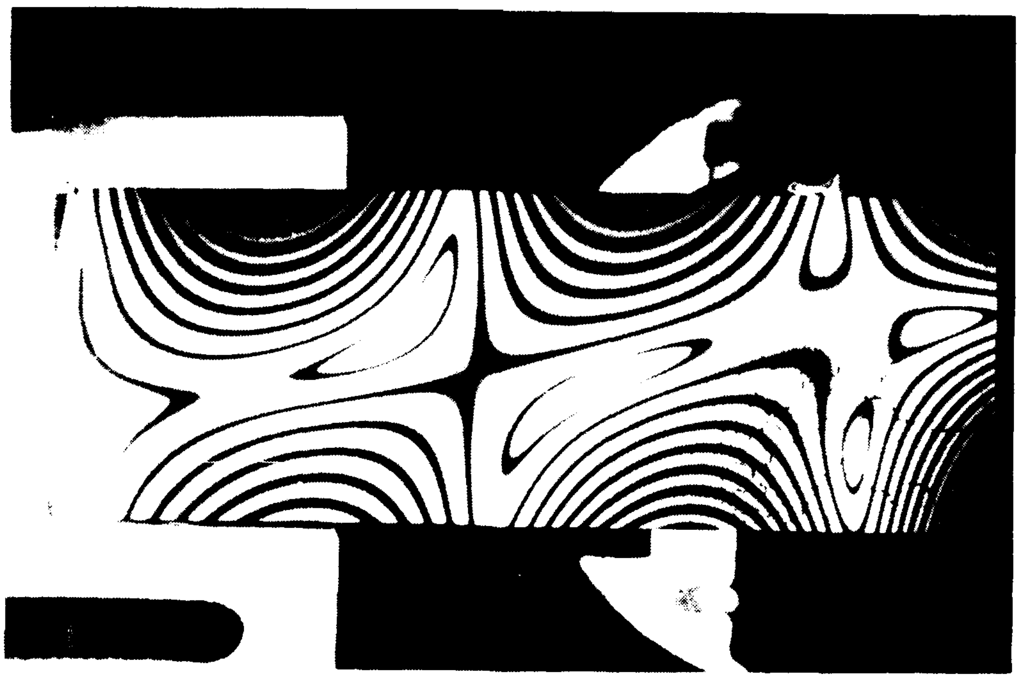


FIG.15 HOLOGRAM AT 2100 Hz FOR UNDAMAGED SPECIMEN

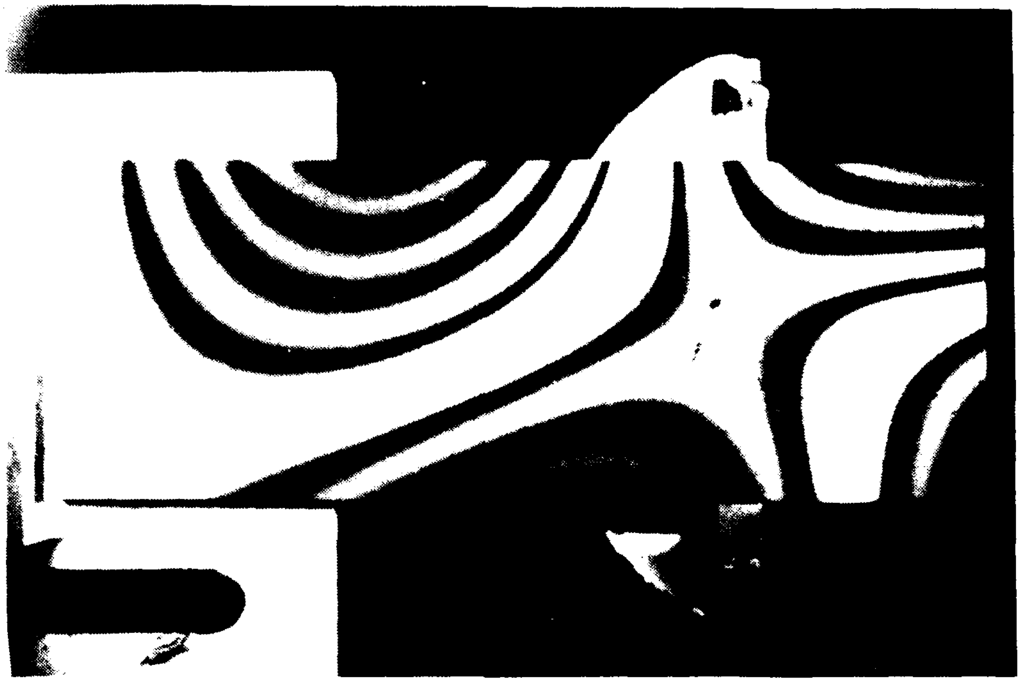


FIG.16 HOLOGRAM AT 1157 Hz FOR DAMAGED SPECIMEN

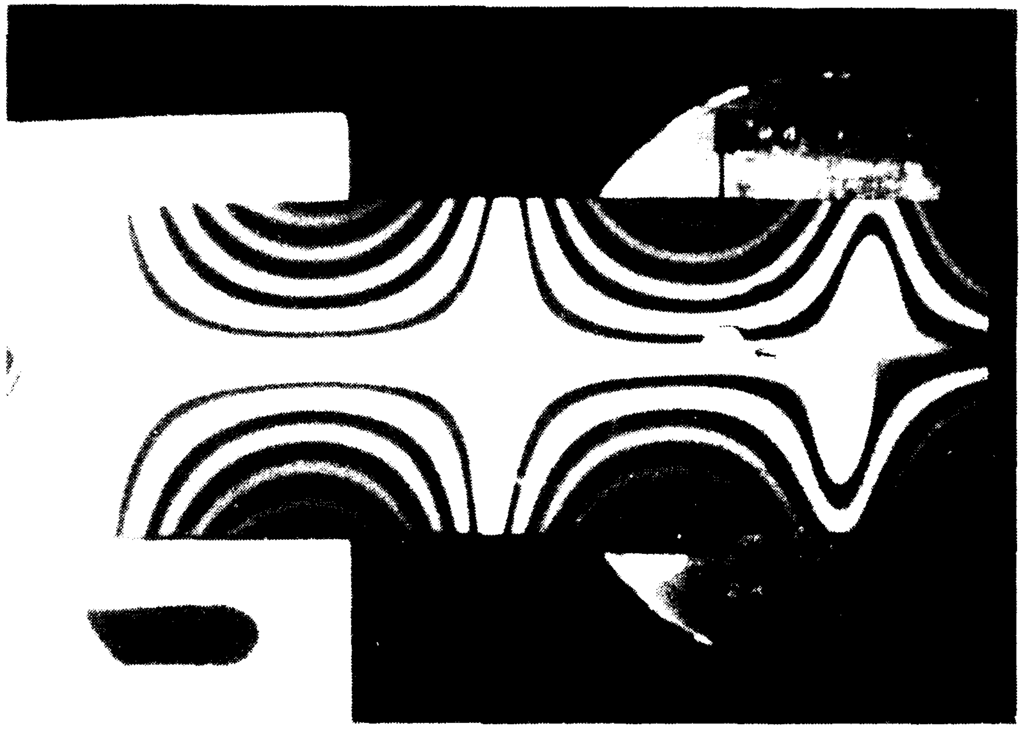


FIG.17 HOLOGRAM AT 2160 Hz FOR DAMAGED SPECIMEN

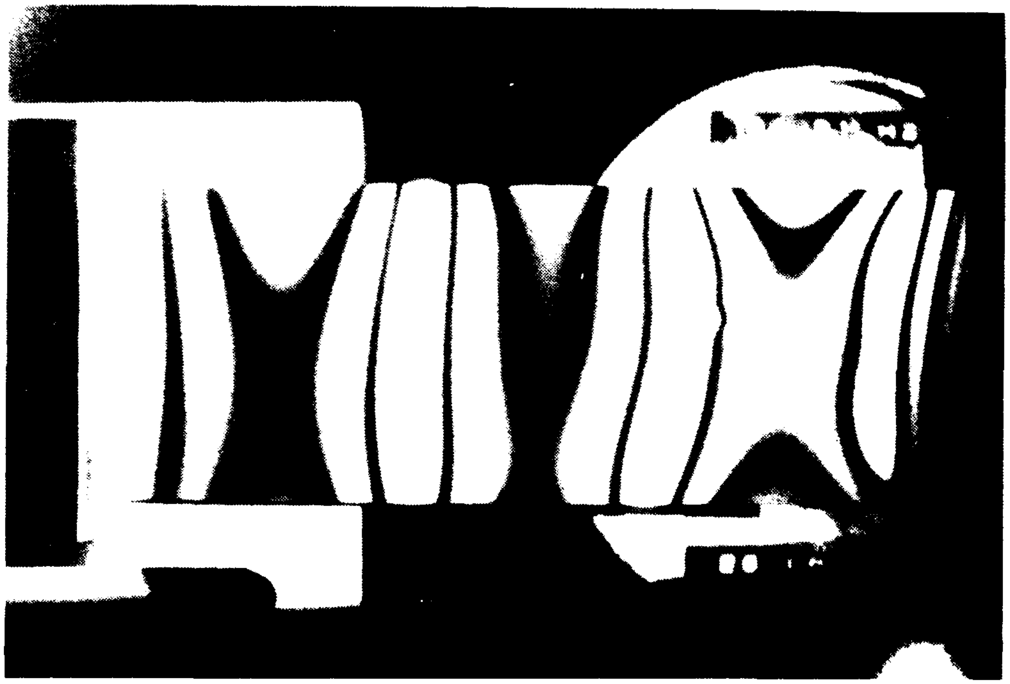


FIG.18 HOLOGRAM AT 2340 Hz FOR DAMAGED SPECIMEN

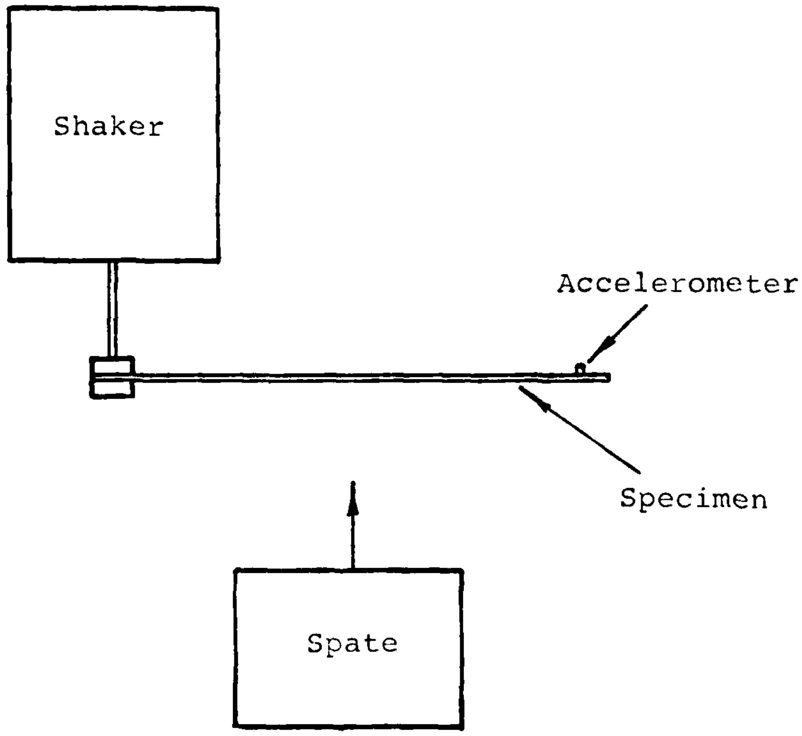


FIG.19 EXPERIMENTAL CONFIGURATION FOR THERMOELASTIC ANALYSIS

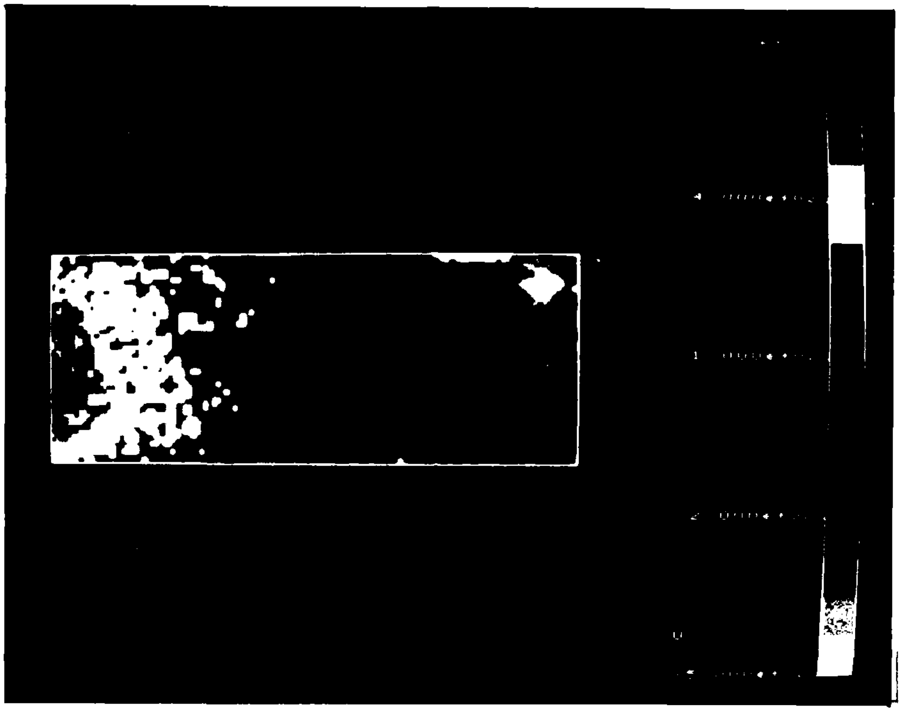


FIG.26 STRESS CONTOUR OF UNDAMAGED SPECIMEN AT FREQUENCY OF 81 Hz.

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Impact damage	Nondestructive testing	11040
Composite materials		
Holographic interferrometry		

Cont'd

16. Abstract

The dynamic response of a graphite/expoxy composite plate has been characterized by a number of techniques to investigate their suitability for detection of barely visible impact damage (BVID). The investigations included single point accelerometer response, time-averaged holographic interferometry and thermoelastic analysis. It was found that the detection of BVID using vibration analysis is complicated by the sensitivity of the analysis to boundary conditions and the means of excitation. Further investigation would require larger specimens to reduce the effects of boundary conditions.

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